Washington University School of Medicine
Digital Commons@Becker

Independent Studies and Capstones

Program in Audiology and Communication Sciences

2012

Subjective and objective measures of adult bimodal users' listening

Roseanna M. Christal
Washington University School of Medicine in St. Louis

SUBJECTIVE AND OBJECTIVE MEASURES OF ADULT BIMODAL USERS' LISTENING

by

Roseanna M. Christal

A Capstone Project
submitted in partial fulfillment of the
requirements for the degree of:

Doctor of Audiology

Washington University School of Medicine
Program in Audiology and Communication Sciences

May 17, 2013

Approved by:
Rosalie Uchanski, Ph.D., Capstone Project Advisor
Lisa Potts, Ph.D., Second Reader

Abstract: Inconsistencies exist between traditional objective measures such as speech recognition and localization, and subjective reports of bimodal benefit. The purpose of this study was to expand the set of objective measures of bimodal benefit to include non-traditional listening tests, and to examine possible correlations between objective measures of auditory perception and subjective satisfaction reports.

Acknowledgements

I would like to thank Dr. Rosalie Uchanski for her support, attention to detail, reassuring guidance and encouragement over the past year. I would also like to extend thanks and appreciation to Dr. Lisa Potts and Dr. Lisa Davidson for their clinical insight, answers to countless questions, and contributions as Second and Third Readers for my Capstone Project. Dr. Amanda Ortmann, clinical audiologists within the Adult Cochlear Implant Division at Washington University, and Sarah Unfried provided a great deal of assistance throughout the recruitment process. Michael Wallendorf offered expertise in the statistical analysis and interpretation of data. Dr. Brent Spehar and Christine Brenner imparted useful information regarding objective measures and data collection. In addition, I would especially like to thank the participants, as they were the heart and motivation behind this study.

The statistical analysis for this study was made possible by Grant Number UL1 RR024992 from the National Center for Research Resources (NCRR), a component of the National Institutes of Health (NIH), and NIH Roadmap for Medical Research. Its contents are solely the responsibility of the authors and do not necessarily represent the official view of NCRR or NIH. Information on NCRR is available at http://www.ncrr.nih.gov/.

Table of Contents

List of Tables and Figures

Abbreviations

APHAB	Abbreviated Profile of Hearing Aid Benefit
ANL	Acceptable Noise Level
BNL	Background Noise Level
CI	Cochlear Implant
CI+HA	Bimodal
CNC	Consonant-Nucleus-Consonant Test
dB	Decibel
DOSO	Device-Oriented Subjective Outcome Questionnaire
HA	Hearing aid
HHIE	Hearing Handicap Inventory for the Elderly
HL	Hearing level
JND	Just Noticeable Difference
MCL	Most Comfortable Level
SNR	Signal to noise ration
PIPSL	Performance Inventory for Profound and Severe Loss
PSI	Pediatric Speech Intelligibility
PTA	Pure tone average
SSQ	Speech Spatial Qualities Questionnaire
SD	Standard deviation
UW-CAMP	University of Washington Clinical Assessment of Music Perception
WU	Washington University
WUSM	Washington University School of Medicine

INTRODUCTION

Recently, cochlear-implant candidacy criteria have expanded such that more individuals than ever before are eligible to receive these devices (National Institute on Deafness and Other Communication Disorders [NIDCD], 2011). This expansion in eligibility criteria is due, primarily, to improvements in cochlear implant (CI) technology. As a result, many patients receiving CIs have aidable hearing in the ear not receiving the CI (Fitzpatrick, Séguin, Schramm, Chénier, & Armstrong, 2009). This situation, when one ear is stimulated electrically via a CI and the other ear acoustically through a conventional hearing aid (HA), is frequently known as “bimodal hearing” or as using “bimodal devices.”

Binaural hearing, or hearing with both ears, offers benefits such as improved localization and speech perception in quiet and noise, when compared to hearing monaurally (Ching, van Wanrooy, & Dillion, 2007). Benefits such as these may be obtained, to some degree, through either bimodal or bilateral CI stimulation. Schafer, Amlani, Paiva, Notari, and Verret (2011) completed a meta-analysis of recent literature, evaluating 42 peer-reviewed articles published from January 2000 to April 2011, to assess whether bilateral and/or bimodal users illustrated significant binaural benefit on measures of adaptive and fixed speech recognition tasks. Specifically, binaural benefit was determined by examining binaural squelch, binaural summation, and the head-shadow effect. The authors reported that bilateral cochlear implant users obtained significant benefit in all three areas of binaural “phenomena,” but that bimodal users only received significant benefit from binaural summation and the head-shadow effect, suggesting a small advantage in the bimodal condition. However, since no analyses of subjective measures were performed, it was difficult to conclude if bilateral CI users perceived an advantage over bimodal users.

Though many recent studies have been published on the hearing abilities of listeners with bimodal devices, many questions remain particularly regarding patients' self-report of the listening benefits of using bimodal devices (Dorman, Gifford, Spahr, & McKarns, 2008; Cullington & Zeng, 2010, Pyschnny, Landwehr, Hahn, Wedel, & Meister, 2011; Fitzpatrick et al., 2009). Most studies using objective measures, such as speech perception and sound localization tests, report better scores for bimodal listening compared to listening with a CI alone (Ching, Incerti, & Hill, 2004; Tyler, Parkinson, Wilson et al., 2002; Ching et al., 2007).

A recent study by Fitzpatrick et al. (2009) illustrated discrepancies or inconsistencies between objective measures and subjective measures (patient satisfaction) with bimodal listening. For example, one subject had poorer scores on the Hearing in Noise Test (HINT) in quiet when listening with bimodal devices than when listening with the CI alone. Yet, this subject preferred full-time HA use with his/her CI. Fitzpatrick et al. concluded that further research was needed to assess how bimodal users' perceived benefit from hearing aid use in real-life situations corresponds to measures of localization and speech perception in laboratory environments. Ching et al. (2004) found similar discrepancies: some subjects demonstrated no bimodal benefit using clinical measures of speech recognition, yet reported improved functioning in real-life situations when wearing both devices.

Anecdotally, there are also differences between objective measures and subjective reports of bimodal benefit. Some patients report much-improved functioning in everyday life with bimodal-device use despite having speech scores that show little or no benefit. And, other patients report little satisfaction with their bimodal devices, yet obtain objective scores that indicate bimodal benefit (Lisa Potts, personal communication). One possible reason for these apparent discrepancies might be that objective measures have been limited primarily to traditional speech recognition and localization tests.

Measures are needed that better reflect bimodal listeners' function in everyday communication environments. A possible example of this is The Acceptable Noise Level Test (ANL). This test is an objective measure that determines an individual's tolerance to background noise. Nabelek, Freyaldenhoven, Tampas, Burchfield, and Muenchen (2006) found that individuals obtaining lower ANL scores (higher tolerance to background noise) were more likely to become successful hearing aid users than those who obtained higher ANL scores. Donaldson et al. (2009) assessed twenty unilateral CI users' speech recognition in noise and noise tolerance levels (ANL) to predict perceived communication abilities. The consequence of background noise on daily communication was evaluated by having each participant complete an aided Abbreviated Profile of Hearing Aid Benefit (APHAB; Cox & Alexander, 1995). A statistically significant relationship between perceived communication difficulties in noise (higher APHAB scores) and poorer tolerance to noise (higher ANL scores) was demonstrated. Donaldson et al. also found no association between speech recognition in noise scores and ANL scores, suggesting that noise tolerance may reveal characteristics of CI users' subjective communication ability that are not measured with objective measures such as speech recognition in noise. At this time, however, no similar study with bimodal users has been done to examine the relation between ANL and subjective communication abilities.

Uchanski et al. (2009) used talker discrimination tasks as part of a test battery for assessing different device conditions in a pediatric case study. Device conditions for this measure included HA only, CI only, CI and HA (bimodal), and both a CI and HA in the same implanted ear, in addition to a HA in the non-implanted ear. Overall, a small improvement was seen in the CI and HA condition versus the cochlear implant alone condition. Spectral resolution provided by the hearing aid may assist bimodal users in real-life listening situations. In addition, since discriminating between talkers' voices is part of everyday communication, talker discrimination tasks may better relate to subjective reports.

Kang et al. (2009) developed the University of Washington Clinical Assessment of Music Perception (UW-CAMP) test to assess music perception abilities in cochlear implant users. Subjective outcome measures were administered to detect correlations between self-report ratings and performance on the UW-CAMP tests. No significant relationship was found between UW-CAMP performance and ratings on the Performance Inventory for Profound and Severe Loss (PIPSL; Owens & Raggio 1988) or the Hearing Handicap Inventory for the Elderly (HHIE; Weinstein & Ventry 1983). Several studies suggest that, in addition to a CI, HAs may provide supplementary information regarding changes in fundamental frequency and enable integration of acoustic and electric stimulation at low frequencies for bimodal users (Dorman et al., 2008; Ching et al., 2007; Kong & Carolyn, 2007). Cochlear implant users' listening abilities, such as music perception, that utilize spectral and temporal cues may improve with the addition of a hearing aid in the non-implanted ear. At present, no studies have examined the relationship between bimodal performance on measures of music perception and subjective reports of bimodal benefit.

Davidson and colleagues are currently investigating the effects of speech perception and ease of listening on cognitive resources in normal and hearing-impaired children. It has been proposed that in more difficult listening situations, individuals with hearing impairment especially, may need to exert greater amounts of perceptual effort to recognize and understand speech, leaving them with fewer resources to process information. The time it takes for an individual to respond to a task, such as speech perception, may be indicative of the effort necessary to execute the task (Gatehouse, 1993).

A reaction time measure designed by Davidson and colleagues at Washington University was used to assess perceptual effort. This task was based on a choice reaction time test developed by Johnson and colleagues (2005). For this test measure, sentences from the Pediatric Speech Intelligibility (PSI) test (Jerger & Jerger, 1982) were presented at 65 decibels (dB) sound pressure level (SPL) in quiet and in the presence of multitalker background noise presented at +5 and +10 signal-to-noise ratios (SNR). Illustrations taken from the PSI test were used to depict the sentence content and were presented on a computer screen before the auditory presentation began. The participant was asked to decide whether the auditory stimulus matched the picture stimulus and respond using a closed-set choice, yes/no. Presently, data have indicated that children with hearing impairment are making correct responses, however, they take significantly longer to listen and respond than their normal hearing counterparts. This appears to be consistent across the quiet, +5, and +10 SNR conditions (Davidson, personal correspondence). Also, the reaction time for the normal hearing group remains similar across the three conditions (quiet, +5 and +10) while the reaction for the HI group is significantly longer for the +5 dB SNR condition than for the quiet condition.

The purpose of this study was to expand the set of objective measures of bimodal benefit to include non-traditional listening tests, and to examine possible correlations between objective measures of auditory perception and subjective satisfaction reports. We believe that non-traditional tests may be more sensitive to bimodal benefit than traditional ones.

METHODS

Participants

Fourteen cochlear implant recipients who currently wore a hearing aid in the non-implanted ear participated in this study. Participants ranged in age from 27 to 80 years, with a mean age of 60 years, and included nine females and five males. Duration of hearing loss for the implanted ear ranged from 19 to 47 years, with a mean of 30.9 years, while duration of hearing loss for the acoustically-aided ear ranged from 19 to 52 years, with a mean of 32.2 years. Mean duration of severe-to-profound hearing loss prior to implantation was 7.9 years, with a range of 2 months to 26 years. Hearing aid use prior to implantation ranged from 6 to 36 years, with a mean duration of 17.9 years. Table 1 contains individual and mean audiologic and demographic information.

Each participant wore an ear-level CI sound processor. Of the 14 participants, 13 had Cochlear Americas' devices; eight used the Nucleus System CP810 processor and five used the Nucleus Freedom sound processor. One participant (P8) had Advanced Bionics' device and used a Harmony processor. In the contralateral ear, various hearing aid models were worn. No adjustments were made to either device, and hence, all testing was performed with the user's current settings and programs. Table 2 contains individual information regarding devices worn, and durations of cochlear implant and contralateral hearing aid use.

Participants' unaided and aided audiometric thresholds were obtained for both ears. Means and standard deviations (SD) of unaided and aided pure tone thresholds of the non-implanted ear, and aided thresholds of the implanted ear at 125-6000 Hz are plotted in Figure 1. Low (125, 250, & 500 Hz) and mid-frequency (500, 1000, & 2000 Hz) unaided pure tone averages (PTA) of the non-implanted ear revealed a mean of 44 dB HL (SD: 17) and 46 dB HL (SD: 18), respectively. Aided PTAs for the contralateral ear revealed a mean threshold of 43 dB

HL (SD: 16) for low frequencies, and 45 dB HL (SD: 14) for mid frequencies. Individual aided and unaided PTAs of the non-implanted ear are provided in Table 3.

The Consonant-Nucleus-Consonant (CNC) Test (Peterson and Lehiste, 1962) was used to assess participants' open-set word recognition abilities in quiet, in only the bimodal (CI+HA) condition, and is considered an overall speech performance measure. Word recognition performance ranged from 24% to 98% correct, with a mean score of 70% correct (SD: 23 pct pts). Figure 2 shows individual percent-correct word scores.

All participants were recruited from the patient population of Washington University School of Medicine Department of Otolaryngology. Each participant was over 18 years of age, a current user of bimodal devices, acquired severe-profound hearing loss post-lingually, used English was his/her primary language, and had open-set speech understanding scores on monosyllabic words greater than ten percent.

Prior to data collection, this study (#201111069) and accompanying materials, received approval from the Institutional Review Board (IRB) and the Washington University School of Medicine Human Research Protection Office (HRPO). Participants signed an informed consent document prior to testing, and were compensated for their time and travel.

Equipment/Test Environment

All testing was completed in an acoustically-treated custom-built soundroom located in the Central Institute for the Deaf Building of the Washington University School of Medicine (WUSM) Campus. Participants were seated approximately one meter away from a Grason Stradler GSI audio speaker at 0° azimuth. A Grason Stradler GSI-61 audiometer was utilized for all tests, and unaided audiometric thresholds were obtained under Telephonics TDH-50P supra-aural headphones. Objective test materials were presented using a Panasonic Toughbook 19

Touch screen laptop, with Windows 7 and Core 2 Duo processing, routed to the aforementioned audiometer.

Calibration

Calibration was performed with a Quest Technologies 1200 Integrating Sound Level Meter. Slow time, A-weighting, with a range of 50-120 dB was used to obtain accurate measurements (in dB SPL) according to prescribed procedures for each objective test. A Quest Technologies QC-20 calibrator was used to calibrate the sound level meter and ensure accuracy of sound level measurements. Daily calibration checks were completed prior to each test session.

Protocol & Test Materials

Prior to all other tests, unaided audiometric thresholds were obtained for the non-implanted ear using the Hughson-Westlake procedure (Carhart & Jerger, 1959), at octave frequencies from 125 Hz to 6,000 Hz. Aided thresholds were obtained in the sound field using warble-tones, with participants in the HA only condition, and then in the CI only condition. If unaided thresholds were 60 dB HL (hearing level) or better at any frequency in the HA ear, a foam plug was placed in that ear during all CI only condition testing.

The CNC test is composed of ten lists, each with 50 phonetically balanced English words, pre-recorded from a single male talker. For this study, one list was used (List 3) and presented at 60 dB SPL in quiet. Participants were asked to repeat the word that was heard. Percent-correct phonemes and words were scored by the examiner.

Following threshold and CNC testing; each listening condition (HA only, CI only, CI+HA) was tested for each objective test, ANL, UW-CAMP, talker discrimination, and reaction time. The order of tests was randomized across participants. The order of testing for listening condition (HA only, CI only, and CI+HA) was also randomized for each participant, and then remained constant throughout the session. All measures were completed in one test session, which lasted approximately 2 hours.

The Acceptable Noise Level (ANL) Test was used to evaluate a listener's response to background noise while listening to speech (Nabelek, Tucker, & Letowski, 1991). The test was administered according to its instructions. First, the presentation level of a pre-recorded story (by a single male talker) is adjusted based on the listener's judgment of his or her most comfortable listening level (MCL). MCL is defined as a "volume" that is comfortable, but not too loud. Then, while the pre-recorded story continues playing at MCL, multitalker babble background noise is turned on and becomes increasingly louder with time. The participant is asked to report the maximum or highest level at which the background noise is still tolerable. This is called the background noise listening level (BNL). ANL is the difference between the MCL and the BNL (i.e., ANL = MCL – BNL, expressed in dB HL) with lower scores indicating a higher tolerance to background noise. Both speech and noise stimuli were presented through the sound-field speaker at 0° azimuth. Participants performed this task in the HA only, CI only, and CI+HA conditions.

The next non-traditional clinical measure used was a Talker Discrimination task (Uchanski et al., 2009). A within-male talker discrimination test was administered to participants in all three conditions (HA only, CI only, and CI+HA). For this task, the participant heard two different sentences presented at 60 dB SPL. He or she was then instructed to respond whether the same talker or two different talkers spoke the two sentences. For a 'same talker' trial, one male talker says two different sentences. For a 'different talker' trial, two different male talkers say the two different sentences. The sentence recordings are drawn from eight different male talkers from the Indiana Multi-Talker Speech Database (Bradlow, Torreta, & Pisoni, 1996). A total of 32 trials (16 'same talker' and 16 'different talkers') were completed for this test per condition, and percent correct responses were calculated.

The third measure used was the UW-CAMP test (Kang et al., 2009). This measure is comprised of three subtests of music perception, namely pitch, melody, and timbre subtests. For this study, only the pitch direction discrimination task was selected; this subtest is not as easily confounded by music training or experience as are the timbre and melody recognition tests. The pitch direction discrimination task measured a patient's ability to detect changes in the pitch of digitally-synthesized musical notes, or complex tones. In each trial, two synthetic notes, which differed in fundamental frequency, were presented sequentially. The participant was asked whether the first or the second note sounded higher in pitch. An adaptive procedure adjusted the difference in fundamental frequency to the just-noticeable difference (JND) threshold in semitones, with lower semitone thresholds indicating better pitch direction discrimination performance (a semitone is the relative difference in frequency between adjacent notes on a piano keyboard). Three interleaved adaptive tracks were used to estimate JND thresholds at three base frequencies (C4, 262 Hz; E4, 330 Hz; G4, 391 Hz).

The reaction time test (Davidson, personal communication) was administered to assess listening effort. A specially-designed response box with three buttons marked with ready, yes or no, was used for this task. The acoustic stimuli (PSI sentences) were presented when the participant hit the "Ready" button on the response box at a level of 60 dB SPL with a +5 dB SNR. Reaction time, in milliseconds, was measured from the onset of the speech stimulus to the moment the participant pressed either the "Yes" or "No" button. This required the participant to first, listen to the acoustic stimuli, and then make a decision about the relationship between what was said and what was seen. Reaction time was calculated for correct answer trials only. Administration for this task was altered for one participant (P11) who had visual deficits. The examiner verbally described the picture on the computer screen and the participant then verbally decided whether the acoustic stimuli agreed with the verbal description. Based on the participant's response, the examiner pressed the corresponding "Yes" or "No" button.

At the end of the test session, participants were given three subjective questionnaires to complete at home and return via pre-paid postal mail. The first questionnaire was the Speech, Spatial and Qualities of Hearing Scale (SSQ) Questionnaire (Gatehouse & Noble, 2004) which examines hearing disabilities across three domains, spatial-hearing, speech-hearing, and quality of hearing. Each category was examined separately, and a total score obtained by combining the scores from all questions within the domain. The Spatial Qualities scale includes questions concerning directional and distance components of listening as well as movement of sound stimuli. The Speech Qualities scale assesses a range of realistic speech-hearing situations including number of people involved in conversation and perceived difficulty in different levels and types of background noise. Naturalness, listening effort across various environments, and segregation of sounds are all aspects of the Qualities hearing scale. Participants were also asked to complete a second questionnaire, the Device-Oriented Subjective Outcome (DOSO) Scale (Cox & Alexander, 2009). This questionnaire assesses the subject's ability to hear speech cues and his/her listening effort. Finally, the third questionnaire was the Washington University (WU) Bimodal Questionnaire, designed to assess bimodal device use and user preferences (see Appendix).

RESULTS

Statistical Analysis

Statistical analyses were performed to determine if significant differences ($p \leq 0.05$) existed between listening conditions (HA only, CI only, and CI+HA) on objective measures. The analysis for comparison of listening conditions was a mixed random effects model with the participant as a random effect (Mixed Procedure SAS 9.3). Overall, no main effect was observed between listening conditions on objective measures and the null hypothesis was not rejected.

The ANL testing showed poorest tolerance for noise in the HA only condition with a mean of 11.00 dB SNR (SD: 4.32), and a range of 16 dB (4 to 20 dB SNR). The CI only condition had a mean of 10.00 dB SNR (SD: 3.42), and range of 12 dB (6 to 18 dB SNR). The bimodal condition revealed the lowest mean ANL value, with a mean of 8.43 dB SNR (SD: 4.59), and a range of 16 dB (2 to 18 dB SNR). Results indicated no significant ANL difference between HA only, CI only, or CI+HA listening conditions [$F(2,26) = 2.22$; $p = 0.1289$]. Individual ANL values per listening condition, as well as group mean and standard deviations, can be found in Figure 3.

For the Within-Male Talker Discrimination task, 32 sentence pairs were presented with either the same talker or different male talkers. Chance level was 50% correct, with 65.5% correct representing the 95% confidence level above which performance was considered reliably better than chance. Overall, mean performance scores varied less than 2% between listening conditions, and therefore, were not statistically different [$F(2,26) = 0.04$; $p = 0.9589$.] Percent-correct scores for the HA only condition ranged from 50% to 88% correct, with a mean score of 66.36% (SD: 10.55 pct pts). Mean scores of 65.86% (SD: 10.65 pct pts) and 67.0% (SD: 14.0 pct pts) were observed for CI only and CI+HA listening conditions, respectively. CI only performance ranged from 47% to 78% correct, and a range of 41% to 80% correct was observed in the CI+HA condition. Figure 4 illustrates individual percent-correct scores per listening condition and the group mean with standard deviations.

UW-CAMP pitch-direction discrimination results are reported in semitones. JND thresholds, in semitones, for each listening condition were obtained via average performance on the three interleaved adaptive tracks, each with varying base frequencies (C4, 262 Hz; E4, 330 Hz; G4, 391 Hz). Lower thresholds indicate better performance (or better pitch-direction discrimination) on this task. A threshold of 1.00 semitone represents the ability to discriminate the relative difference in frequency between adjacent notes on a piano keyboard. The HA only condition revealed the highest mean threshold of 3.39 semitones, (SD: 3.21), with a range of 0.72 to 10.74 semitones. In the CI only condition, a mean threshold of 3.07 semitones (SD: 2.0) was found, with a range of 0.54 to 7.07 semitones. CI+HA condition thresholds ranged from 0.54 to 7.72 semitones, with a mean of 3.01 semitones (SD: 2.22). Results demonstrated marked variability between participants and no significance was found between listening conditions [F (2,26) = .13; p = .8784]. Individual JND thresholds per listening condition can be found in Figure 5.

Mean reaction times ranged from 2443 milliseconds (ms) (SD: 873) in the CI+HA condition to 2985 ms (SD: 2007) in the HA only condition. In the CI only condition, a mean reaction time of 2827 (SD: 1410) was found. Individual and group mean reaction times for each listening condition are shown in Figure 6. Due to inaudibility of the stimulus in the aided non-implanted ear, P8's reaction time for the HA only condition was not included in the analysis. Variation among participants was evident, and there were no significant differences between HA only, CI only, or CI+HA listening conditions on reaction time [F (2,25) = 1.18; p = .3238].

Speech, Spatial, and Qualities of Hearing Questionnaire

The three scales of the SSQ were analyzed separately to assess participant perception of bimodal use and benefit across a variety of realistic listening situations. On a scale of 1 through 10, a rating of 1 indicates greatest difficulty experienced, and a rating of 10 is consistent with no perceived handicap. The Spatial scale had the lowest mean rating score of 4 (SD: 2). The speech scale had a mean rating score of 5 (SD: 1). The Qualities of hearing scale was rated highest overall, with a mean rating score of 6 (SD: 2). Mean (and SD) rating scores of the SSQ are shown in Figure 7.

DOSO

The two categories of the DOSO, speech cues and listening effort, were analyzed. Each category was examined separately and scored based on total values of all questions within each domain. Ratings range from 1 to 7, where 1 indicates no benefit received from wearing both devices (CI+HA) and 7 indicates tremendous benefit received (versus not wearing devices at all). Listening effort revealed a mean rating score of 5 (SD: 1), while speech cues had a mean score of 4 (SD: 1). Mean (and SD) rating scores of the DOSO categories are shown in Figure 8.

WU Bimodal Questionnaire

Individual participant responses are shown in Tables 4 and 5. All participants reported a difference in hearing when wearing their HA in addition to their CI. Participants included descriptions of sound being more natural, less tinny, more balanced between ears, and easier to locate when wearing the HA in addition to the CI. When asked what percentage of time both devices were worn together, ten participants reported using both devices 95% of the time or higher. Three participants reported using both devices together 80-85% of the time, and one participant (P14) reported wearing her hearing aid 90%, but only wearing both devices together 70% of the time. This participant preferred only wearing the HA during activities such as working on the computer, completing yard work and riding/driving in the car because her CI picked up "the clicking of the [computer] keys" and other extraneous noises. Participants were also asked to rate benefit received when wearing both devices, eight participants gave a rating of 10 (Extremely), followed by two participants who individually gave ratings of 8 and 9, respectively, and finally four participants indicated they received some benefit, with ratings between 5 and 7.

Correlation Analysis: Objective Measures and Subjective Reports

A correlation analysis was completed to examine associations between bimodal performance on objective measures and rating scores on subjective reports. Associations were estimated with Pearson correlation tests (Corr Procedure SAS 9.3). Each category of the SSQ and DOSO was compared to bimodal performance on measures of Within-Male Talker Discrimination, UW-CAMP pitch-direction discrimination, reaction time, CNCs, and ANL. Results from this analysis are shown in Table 6. Reaction time results from Participant 2 were not included in the correlation analysis, as they tended to overestimate the significance of this measure. A significant correlation was found between the DOSO Listening Effort category and the ANL test ($r = -0.63$, $p = 0.02$). No other significant correlations were demonstrated ($p > 0.13$).

Another correlation analysis was completed to examine the relationship between rating scores on the Speech domain of the SSQ and the Speech Cues category of the DOSO. A marginally significant correlation was found to exist between the two subjective categories ($r = 0.50$, $p = 0.08$).

DISCUSSION

Some bimodal users show discrepancies between objective performance scores achieved in the clinic and subjective reports of bimodal use and satisfaction. Understanding perceived contributions offered by the addition of an acoustically stimulated non-implanted ear, and having the ability to evaluate those contributions objectively would benefit both the clinician and patient. The purpose of this study was to expand the set of objective measures of bimodal benefit to include both traditional and non-traditional clinical listening tests. Then, to explore possible correlations between objective measure performances and subjective satisfaction reports.

Findings from this study were similar to those of Ching et al. (2004) and Fizpatrick et al. (2009). Although some participants did not demonstrate bimodal benefit on objective measures, improved functioning in real life was reported. In addition, results from the current study demonstrated that certain individuals who showed little or no benefit in the bimodal condition compared to the CI only listening condition still preferred to wear both devices together. For example, Participant 7 had little or no improvement in the CI+HA condition compared to the other listening conditions across all objective measures. However, in response to how often the hearing aid was worn in addition to the cochlear implant via the WU Bimodal Questionnaire, the participant reported 95% of the time. Also, when asked to rate how much benefit was received when wearing both devices, a rating of 8 was given. Another participant (P3) illustrated bimodal benefit on only one objective measure, Within-Male Talker Discrimination. Yet, P3 reported a rating of 10 in response to how much benefit was received when wearing both devices.

Donaldson and colleagues (2009) examined correlations between ANL scores and subjective measures in 20 unilateral CI users. They found a mean dB SNR of 8.4 on the ANL test. The mean value for the CI only condition in the current study was within 2 dB of these findings (10.0 dB SNR) and the CI+HA condition revealed a similar mean value of 8.43 dB SNR. Donaldson et al. (2009) suggested noise tolerance might reveal characteristics of CI users' subjective communication ability that are not measured through objective tasks. Results from the current study displayed a significant relationship between bimodal performance on the ANL and Listening Effort (DOSO). The Listening Effort category of the DOSO focused on bimodal device contributions to the clarity of the sound, ability to distinguish and recognize voices, and reduction of miscommunications during conversation. The relation between ANL and Listening Effort may be an illustration of noise acceptance revealing a characteristic of bimodal users' subjective communication ability that is not observed by means of typical objective measures.

While ANL values, overall, were found to be insignificantly different across listening conditions, examining ANL scores at an individual level is of interest. An ANL of 6 dB SNR or better indicates a greater tolerance to background noise and increases the probability of successful HA use (Nabelek et al., 1991; Nabelek, Tampas, & Burchfield, 2004; Nabelek et al., 2006). A large ANL of 14 dB SNR or greater shows a much poorer acceptance to background noise and decreases the probability of device acceptance. Several participants tolerated a much higher noise level in the CI+HA condition compared to their CI only and HA only conditions, as shown in Figure 4. For example, three participants (P4; P6; P10) demonstrated a bimodal improvement of 6-8 dB SNR compared to listening with either device alone. In contrast, some participants (P1; P3; P9) did not benefit from bimodal listening, and in fact, showed poorer acceptance of background noise than was observed in the HA only or CI only conditions. Yet as a group, participants had positive self-report ratings regarding Listening Effort. Participants that performed worse in the bimodal condition rated themselves similarly to the participants that performed best. While a significant correlation was found between ANL and DOSO Listening

Effort, inconsistencies still exist between perceived benefit and objective performance with bimodal listening.

No significant differences were found between listening conditions on measures of Within-Male talker discrimination and pitch direction discrimination (UW-CAMP). Cullington and Zeng (2010) compared bimodal and bilateral CI users on measures of music perception, affective prosody discrimination, talker discrimination, and speech recognition in noise. These authors hypothesized that better spectral resolution at lower frequencies provided by residual hearing in the non-implanted ear would result in bimodal CI users outperforming bilateral CI users on tasks requiring good pitch perception. Yet, on pitch-related tasks, such as talker discrimination and music perception, Cullington and Zeng found that the mean scores of bimodal users were similar to the mean scores of bilateral users, indicating no significant difference between these two populations. Factors such as hearing aid technology or audibility in the hearing aid ear could explain why limited contributions were found.

Results from the reaction time test were not significantly different amongst listening conditions and not significantly correlated with any subjective measures. Still, differences between mean reaction times per listening condition were noted. The HA only condition revealed the slowest mean reaction time of 2985 ms (SD: 2007 ms), followed by the CI only condition at 2827 ms (SD: 1410 ms). With a mean reaction time of 2443 ms (SD: 873 ms), the bimodal listening condition revealed the fastest reaction time. These results, while not statistically significant, suggest less listening effort is needed when participants are wearing both devices together versus wearing only their CI or HA.

Objective tasks varied in presentation level. For the ANL and UW-CAMP tests, the examiner adjusted presentation levels, based on participant feedback, to a most comfortable listening level. Other tests were presented at a standard presentation level and could not be adjusted. As a result, audibility of the stimulus may have been a factor for some participants. The reaction time and Within-Male Talker Discrimination test materials were presented at a level of 60 dB SPL. Table 3 illustrates two participants (P8; P10) who had aided PTAs at low and mid frequencies greater than 50 dB HL, and hence, stimulus levels for these tests were near or worse than threshold for these subjects. This may have affected performance in both the HA only and CI+HA conditions due to inaudibility of the stimulus.

Some participants showed greater difficulty on objective measures than others. In this regard, results from participants P1 and P2 are of interest. P1 received the lowest CNC bimodal word score of 24% correct, followed by P2 at 30% correct. Both participants were poorer performers on measures of within-male talker discrimination and reaction time. Seemingly consistent with those results low subjective ratings (3 or worse) were given when asked about following conversations in larger groups or communicating in the presence of background noise such as fan noise or reverberant spaces. Yet, across SSQ and DOSO domains, P2 gave the lowest average ratings overall, while P1 was within 1 point of the mean for all subjective reports. This example illustrates the effects of individual variability and that results may reflect other factors such as personality and cognitive abilities.

It might be expected that a survey designed to assess hearing handicaps and disabilities, such as performance in background noise, would correlate with objective performance measures that quantitatively assess these abilities. Yet, for this study, only one significant correlation was found. A few possible explanations follow. It might be that these newly-explored non-traditional objective measures are simply not sensitive measures of bimodal benefit and therefore, will not correlate with subjective reports. Also, other aspects of participants, such as personality and cognitive abilities, were not accounted for in the subjective questionnaires and could be major factors in self-reported benefit. Over half the participants in this study reported, in the WU Bimodal Questionnaire, that they received extreme benefit from wearing both devices together. And, all participants reported at least some benefit from bimodal listening. Yet, bimodal benefit was not observed through analysis of objective measures.

The results of the current study could also be affected by other factors related to the devices themselves. Verification of the CI and HA was evaluated through aided sound field thresholds. Participants used their current devices and everyday use settings. Most participants received hearing aid and cochlear implant services from the WUSM and were therefore programmed according to specific evidence-based clinical procedures. Research efforts continue, however, on evaluating various bimodal fitting strategies. Results from a recent pediatric bimodal study conducted at Washington University revealed that bimodal benefit across a number of outcome measures varied with different hearing aid frequency response settings (Davidson et al., 2012).

Other factors to consider in this study are demographic and audiologic variables. Years of CI use, years of severe-to-profound hearing loss prior to implantation, years of hearing aid use prior to implantation, years of hearing loss in the non-implanted ear, years of hearing aid use in the non-implanted ear, and sound processor and hearing aid all vary amongst these participants. These variables and others may have contributed to overall performance on objective measures across all listening conditions, but were not examined due to the small sample size. In addition, all tests were performed in a custom-built, acoustically-treated soundroom. Due to limited resources, a single- or double-walled sound booth was not available for this study. This less-than-ideal acoustic environment may have contributed to elevated sound field thresholds and increased ambient noise levels. Finally, the power to detect significant changes may have been limited by the relatively small sample size (N=14). Additionally, although a small sample size increases the chance of outliers skewing results, in the current study, an attempt was made to exclude extreme outliers or invalid measurements.

The results found from this study may motivate further investigation into the relations between objective measures of bimodal listening and subjective satisfaction reports. Inconsistencies between objective and subjective measures, as demonstrated in this study, do exist. More research is needed to evaluate the sensitivity of objective measures to bimodal benefit and secondly, to study relations between objective measures and subjective reports of bimodal listening. If clear correlations are eventually found, then guidelines could be established regarding the success or difficulty that may be expected for individuals who receive bimodal stimulation.

References

Bradlow, A. R., Torretta, G. M., & Pisoni, D. B. (1996). Intelligibility of normal speech I: Global and fine-grained acoustic-phonetic talker characteristics. *Speech Communication, 20*(3-4, Dec), 255-272.

Carhart R., & Jerger J. (1959). Preferred method of clinical determination of pure tone thresholds. *J Speech Hearing Disord*, *24,* 330-345.

Ching, T.Y.C., Incerti, P., & Hill, M. (2004). Binaural benefits for adults who use hearing aids with cochlear implants in opposite ears. *Ear Hear*, *25,* 9-21.

Ching, T.Y.C., van Wanrooy, E., &Dillon, H. (2007). Binaural-bimodal fitting or bilateral implantation for managing severe to profound deafness: a review. *Trends in Amplif, 11*(3), 161-192.

Cox, R.M., Alexander, G.C., Xu, J. (2009). Development of the device oriented subjective outcome scale (DOSO). Annual Meeting of the American Auditory Society. Retrieved August 14, 2011, from http://www.memphis.edu/ausp/harl/publications.htm#posters.

Cullington, H. (2012). Bimodal or bilateral? Do we know the answer?. *The Hearing Journal, 65*(3), 14-15.

Cullington, H.E., & Zeng, F.G. (2010). Comparison of bimodal and bilateral cochlear implant users on speech recognition with competing talker, music perception, affective prosody discrimination, and talker identification. *Ear Hear, 32*(1), 16-30.

Davidson, L., Cadieux, J., Brenner, C., et al. (2012). Effects of hearing aid frequency response setting in children with bimodal device fittings. Annual Meeting of the American Auditory Society, 2012.

Donaldson, G.S., Chisolm, T.H., Blasco, G.P., Shinnick, L.J., Ketter, K.J., & Krause, J.C. (2009). BKB-SIN and ANL predict perceived communication ability in cochlear implant users. *Ear Hear, 30*(4), 401-410.

Dorman, M.F., Gifford, R.H., Spahr, A.J., McKarns, S.A. (2008). The benefits of combining acoustic and electric stimulation for the recognition of speech, voice and melodies. *Audiol Neuro-otol, 13,* 105-112

Fitzpatrick, E.M., Sequin, C., Schramm, D., Chenier, J., & Armstrong, S. (2009). Users' experience of a cochlear implant combined with a hearing aid. *Inter Journ Aud, 48*, 172-182.

Gatehouse, S. (1993). Role of perceptual acclimatization in the selection of frequency responses for hearing aids. *J Am Acad Audiol, 4*(5), 296-306.

Gatehouse, S., & Noble, W. (2004). The speech, spatial, and qualities of hearing scale (SSQ). *Int J Audiol,* 43, 85-99.

Gosselin, P.A., & Gagné, J.P. (2010). Use of dual-task paradigm to measure listening effort. *Can J Speech Lang Pathol Audiol, 34*(1), 43-51.

Jerger, S. & Jerger, J. (1982). Pediatric speech intelligibility test: performance-intensity characteristics. *Ear Hear, 3*(6), 325-334.

Johnson, K. C., Wygonski, J. J., & Eisenberg, L. S. (2005). Choice reaction time (CRT) in assessing pediatric word and sentence recognition. Paper presented at the 10th Symposium on Cochlear implants in Children in Dallas, Texas.

Kang, R., Nimmons, G.L., Longnion, J., et al. (2009). Development and validation of the University of Washington clinical assessment of music perception test. *Ear Hear*, *30*(4), 411-418.

Kong, Y.Y., & Carolyn, R.P. (2007). Improved speech recognition in noise in stimulated binaurally combined acoustic and electric stimulation. *J Acoust Soc Am, 117,* 3717-3727.

Nabelek, A.K., Tucker, F.M., & Letowski, T.R. (1991). Toleration of background noises: relationship with patterns of hearing aid use by elderly persons. *J Speech Hear Res, 34*(3), 679-685.

Nabelek A.K., Tampas J.W., & Burchfield SB. (2004) Comparison of speech perception in background noise with acceptance of background in aided and unaided conditions. *J Speech Lang Hear Res, 47*, 1001–1011.

Nabelek, A.K., Freyaldenhoven, M.C., Tampas, J.W., Burchfield, S. B., & Muenchen, R.A. (2006). Acceptable noise level as a predictor of hearing aid use. *J Am Acad Audiol*, *17*, 626-639.

National Institute on Deafness and Other Communication Disorders. (2011). *Cochlear implants* (NIH publication No. 11-4798). Bethesda, MD. Retrieved September 14, 2011, from http://www.nidcd.nih.gov/health/hearing/pages/coch.aspxhttp://www.nidcd.nih.gov/health/hearing/coch.htm

Owens E., & Raggio M. (1988) Performance inventory for profound and severe loss (PIPSL). *J Speech Hear Disord, 53*,42–56.

Peterson, G.E., & Lehiste, I. (1962). Revised CNC lists for auditory tests. *J Speech Hear Disord, 27*, 62-70.

Potts, L.G., Skinner, M.W., Litovsky, R.A., Strube, M.J., & Kuk, F. (2009). Recognition and localization of speech by adult cochlear implant recipients wearing a digital hearing aid in the nonimplanted ear (bimodal hearing). *J Am Acad Audiol,* 20(6), 353-373.

Pyschnny, V., Landwehr, M., Hahn, M., Wedel, H.V., & Meister, H. (2011). Bimodal hearing and speech perception with a competing talker. *J Speech Lang Hear Res*. [Epub ahead of print].

Schafer, E.C., Amlani, A.M., Paiva,D., Nozari, L. & Verret, S. (2011). A meta-analysis to compare speech recognition in noise with bilateral cochlear implants and bimodal stimulation. *Int J Aud, 50,* 871-880.

Tyler, R.S., Parkinson, A.J., Wilson, B.S. et al. (2002). Patients utilizing a hearing aid and a cochlear implant: speech perception and localization. *Ear Hear*, *23*, 98-105.

Uchanski, R.M., Davidson, L.S., Quadrizius, S., et al. (2009). Two ears and two (or more?) devices: a pediatric case study of bilateral profound hearing loss. *Trends Amplif*, *13(*2), 107-123.

Ullauri, A., Crofts, H., Wilson, K., & Titley, S. (2007). Bimodal benefits of cochlear implant and hearing aid (on the non-implanted ear): a pilot study to develop a protocol and a test battery. *Cochlear Implants Int, 8*(1), 29-37.

Weinstein B.E., & Ventry I.M. (1983) Audiologic correlates of hearing handicap in the elderly. *J Speech Hear Res*, *26*,148–151.

Table 1: Individual audiologic and demographic information. Means and standard deviations are provided at the bottom of the table.

Subject ID	Gender	Age	Implanted Ear	Years of HL (CI Ear)	Years of HL (HA Ear)	Years of Severe to Profound HL (CI Ear)	Years of HA use (CI Ear)	Etiology
P1	F	78	Left	45	45	2	6	Meniere's Disease
P2	M	72	Left	47	47	0.2	24	Unknown
P3	F	80	Right	19	19	1	7	Hereditary
P4	F	27	Right	20	20	1	6	Unknown
P5	F	49	Left	28	28	1	24	Sudden SNHL
P6	M	54	Right	38	38	4	21	Unknown
P7	M	64	Right	27	27	6	22	Hereditary
P8	F	49	Left	20	20	1	17	Unknown
P9	M	79	Right	20	20	5	6	Unknown
P10	F	71	Right	20	42	1	8	Meniere's Disease
P11	F	58	Left	38	52	15	36	Usher's Type II
P12	F	52	Left	30	30	30	24	Trauma
P13	M	47	Left	42	24	18	17	Unknown
P14	F	64	Right	39	39	26	33	Otosclerosis
MEAN		60.3		30.9	32.2	7.9	17.9	
Standard Deviation		15		10	11	10	10	

Figure 1: Mean aided pure tone thresholds for the implanted and non-implanted ears, and unaided pure tone threshold means of the non-implanted ear, from 125-6000 Hz.

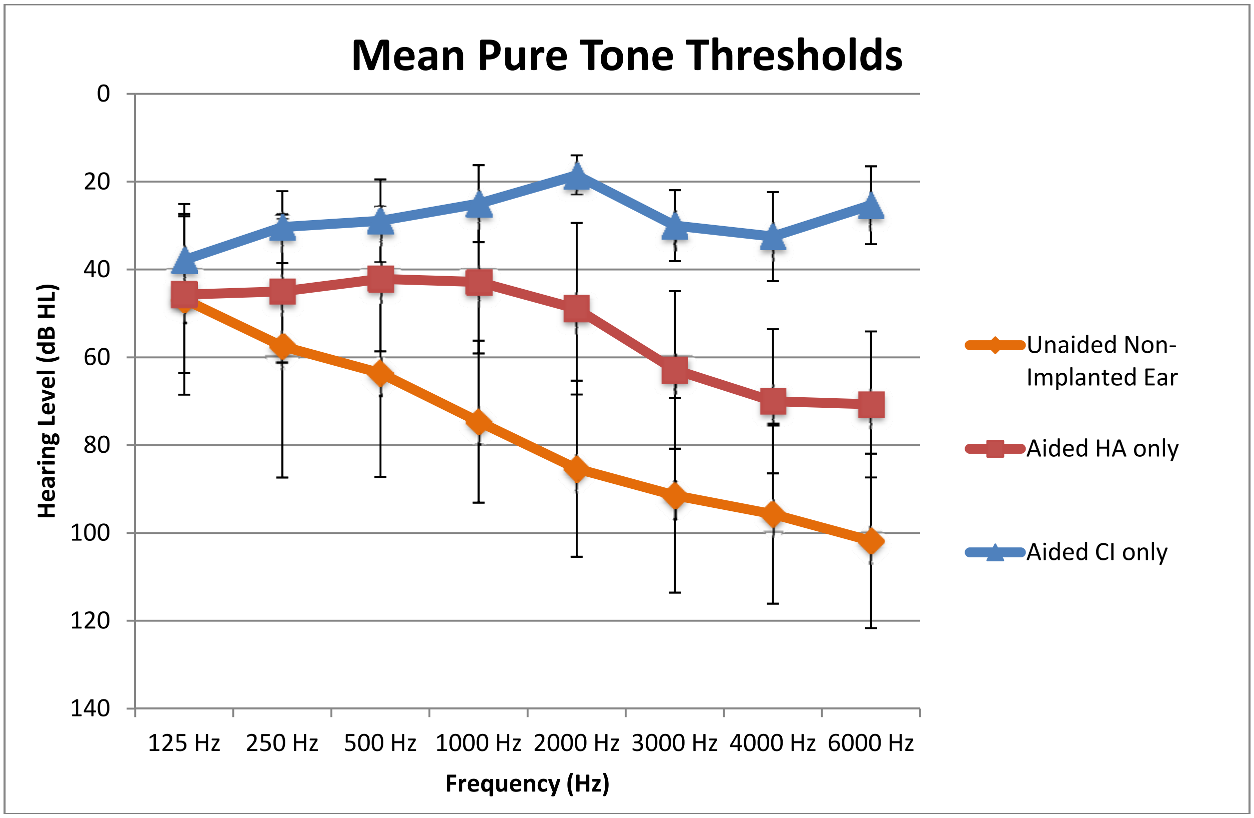

Figure 2: Individual and mean CNC word scores (% correct) in the bimodal listening condition. The error bar represents ±1 standard deviation.

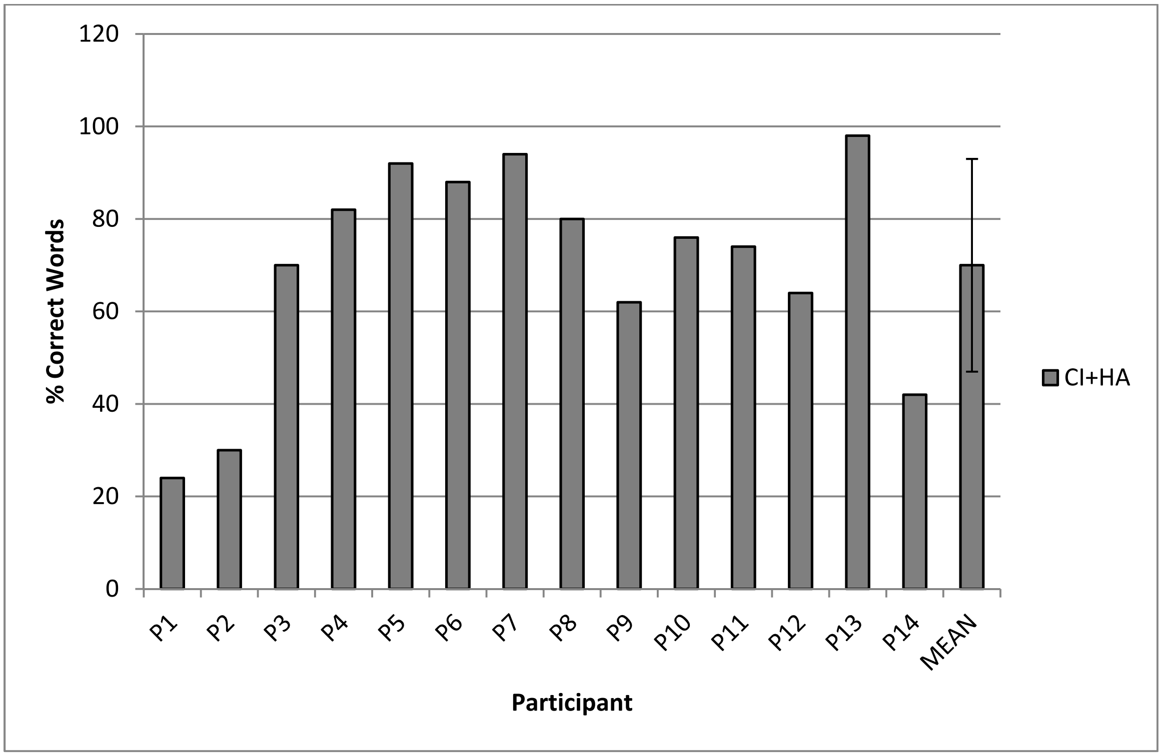

Table 2: Individual information regarding devices worn, and duration of cochlear implant and non-implanted ear hearing aid use. Means and standard deviations are listed at the bottom of the table.

Subject ID	Processor	Years of CI Use	Hearing Aid Model	Years of HA use (HA Ear)
P1	CP810	2	Sonic Innovations Varicom ITE*	12
P2	Freedom	3	ReSound Azure	19
P3	CP810	9	Widex Senso Vita 38	17
P4	CP810	1	ReSound Dot	7
P5	Freedom	4	Widex Diva 19	28
P6	Freedom	9	Widex Senso Vita 38	30
P7	Freedom	5	Phonak Exélia Art	27
P8	Harmony	3	Oticon Vigo Pro	20
P9	Freedom	6	Phonak Naída V UP	14
P10	CP810	0.5	Phonak Naída V UP	22
P11	CP810	2	Phonak Naída V UP	52
P12	CP810	2	Widex Inteo 19	29
P13	CP810	1	Phonak Ambra	14
P14	CP810	2	Phonak Naída V UP	28
MEAN		3.5		22.8
Standard Deviation		3		11

*Only P1 wore an in-the-ear (ITE) HA, all other participants wore behind-the-ear (BTE) receiver-in-the-aid (RITA) devices.

Table 3: Individual aided and unaided PTAs of the non-implanted ear. Group mean and standard deviations are listed at the bottom of the table.

Subject ID	**Non-implanted Ear**	**Unaided Low Frequency PTA (.125, .25, .5 KHz) dB HL**	**Aided Low Frequency PTA (.125, .25, .5 KHz) dB HL**	**Unaided Mid Frequency PTA (.5, 1, 2 KHz) dB HL**	**Aided Mid Frequency PTA (.5, 1, 2 KHz) dB HL**
P1	R	68	67	62	42
P2	R	30	35	63	48
P3	L	98	38	117	58
P4	L	55	47	58	37
P5	R	27	25	77	42
P6	L	77	32	85	48
P7	R	37	43	63	32
P8	R	68	72	93	85
P9	L	53	45	82	35
P10	L	62	63	68	52
P11	R	62	55	70	38
P12	R	50	30	78	47
P13	R	10	20	38	25
P14	L	87	48	88	37
MEAN		55	43	75	45
STANDARD DEVIATION		24	16	19	14

Figure 3: Individual and mean ANL values for each listening condition. Participant order based on bimodal performance. Error bars represent ±1 standard deviation.

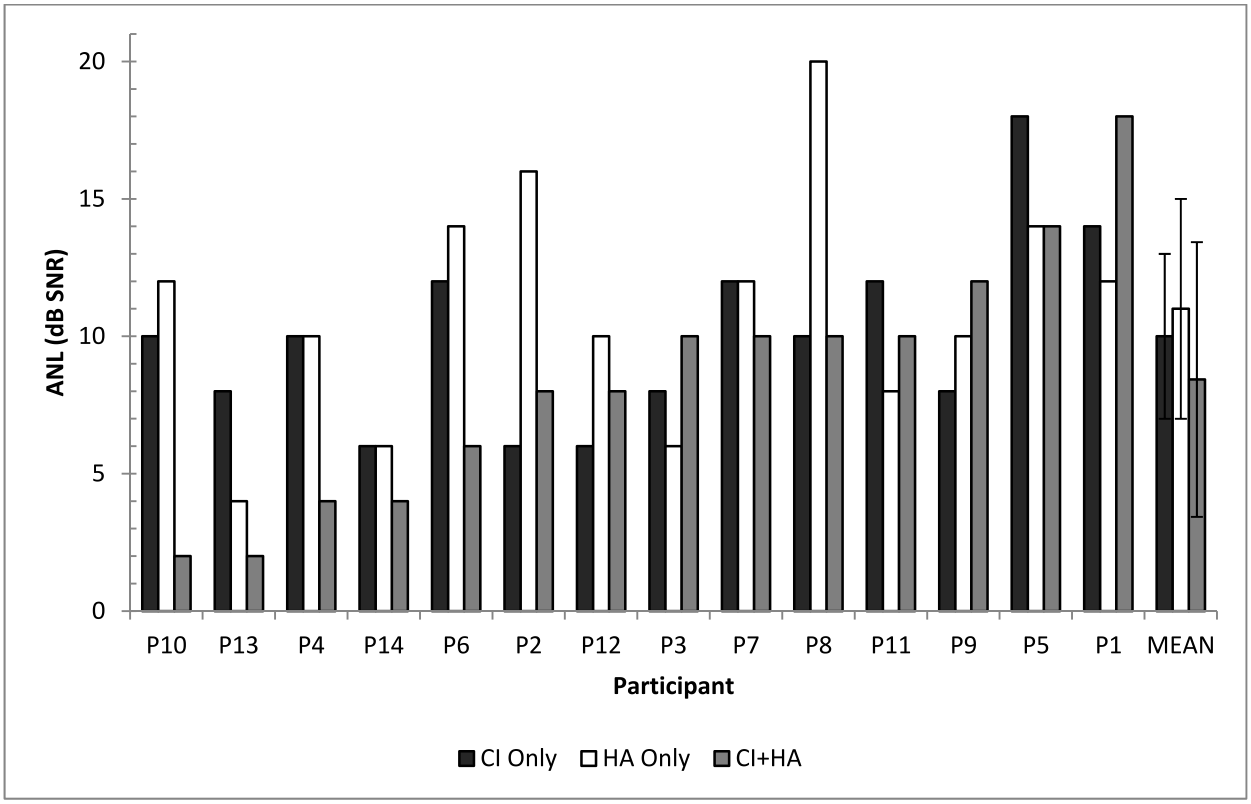

Figure 4: Individual and mean male talker discrimination scores (% correct) for each listening condition. Participant order based on bimodal performance. Error bars represent ±1 standard deviation.

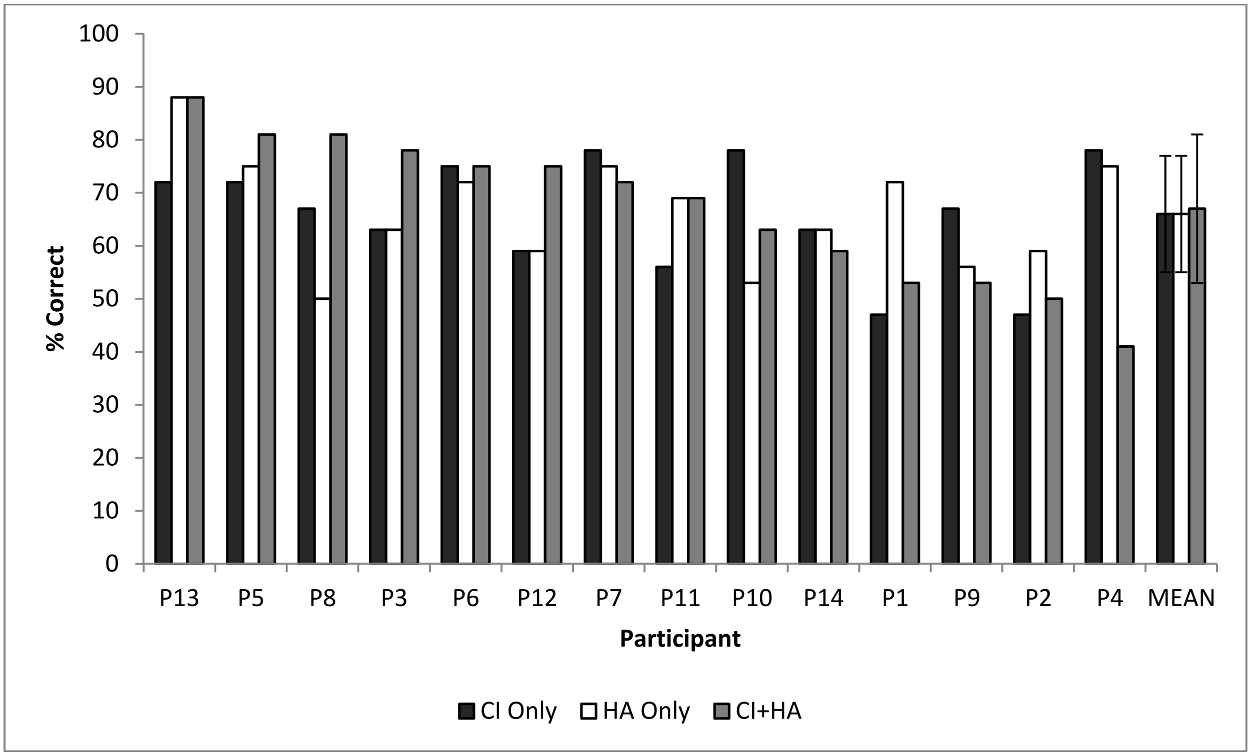

Figure 5: Individual and mean JND thresholds (in semitones) for each listening conditions. Participant order based on bimodal performance (lower semitone scores indicating better performance). Error bars represent ±1 standard deviation

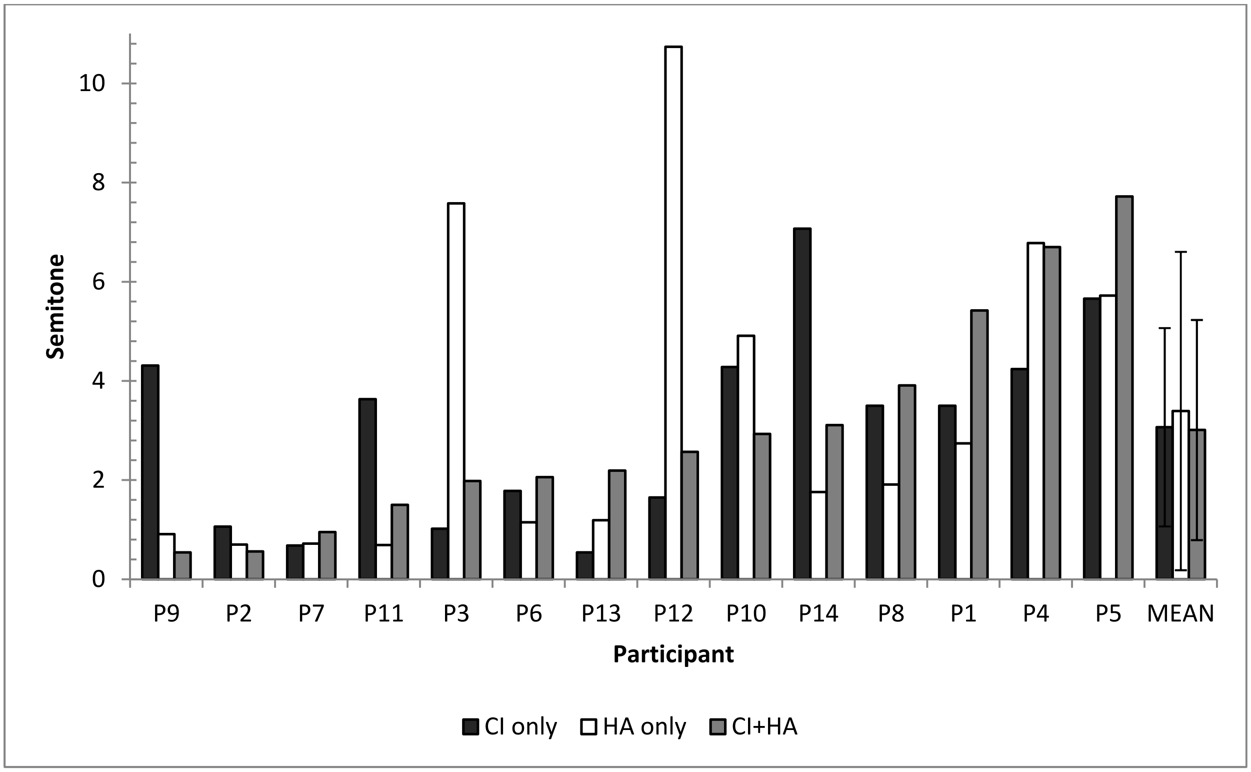

Figure 6: Individual mean reaction time (in milliseconds) of correct responses for each listening condition. Participant order based on bimodal performance. Error bars represent ±1 standard deviation.

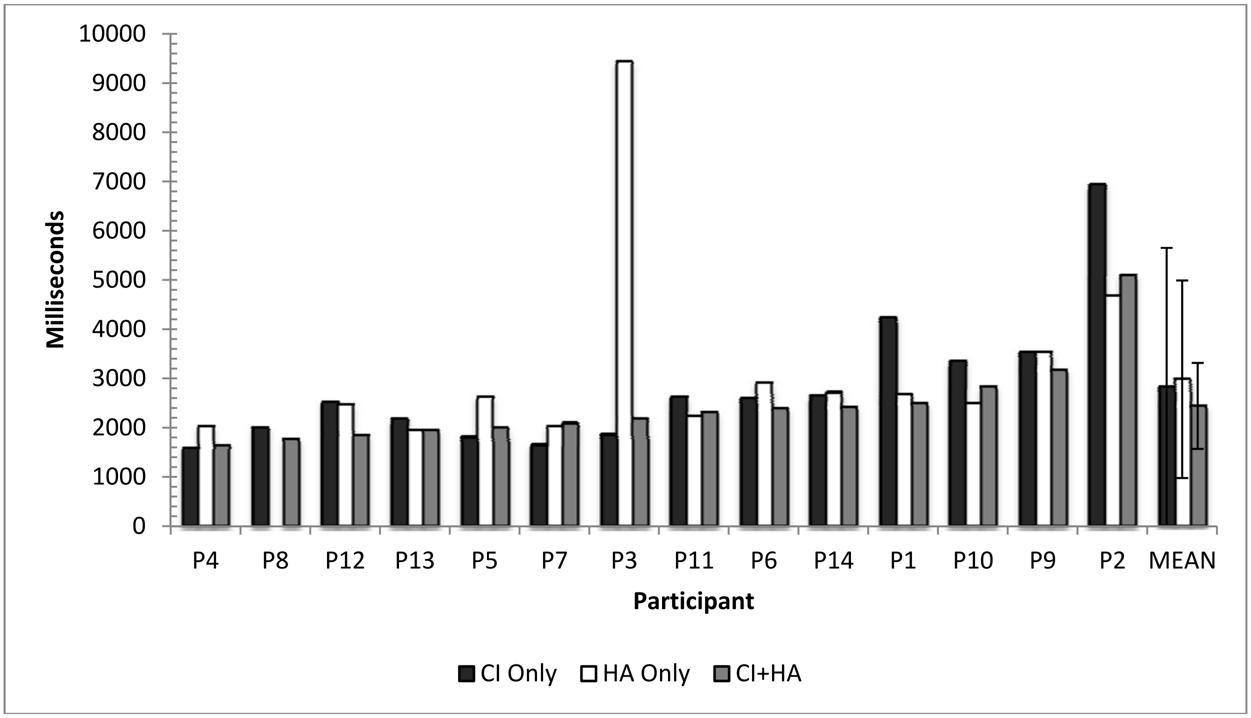

Figure 7: Mean SSQ scores for the bimodal listening condition. Error bars represent ± 1 standard deviation.

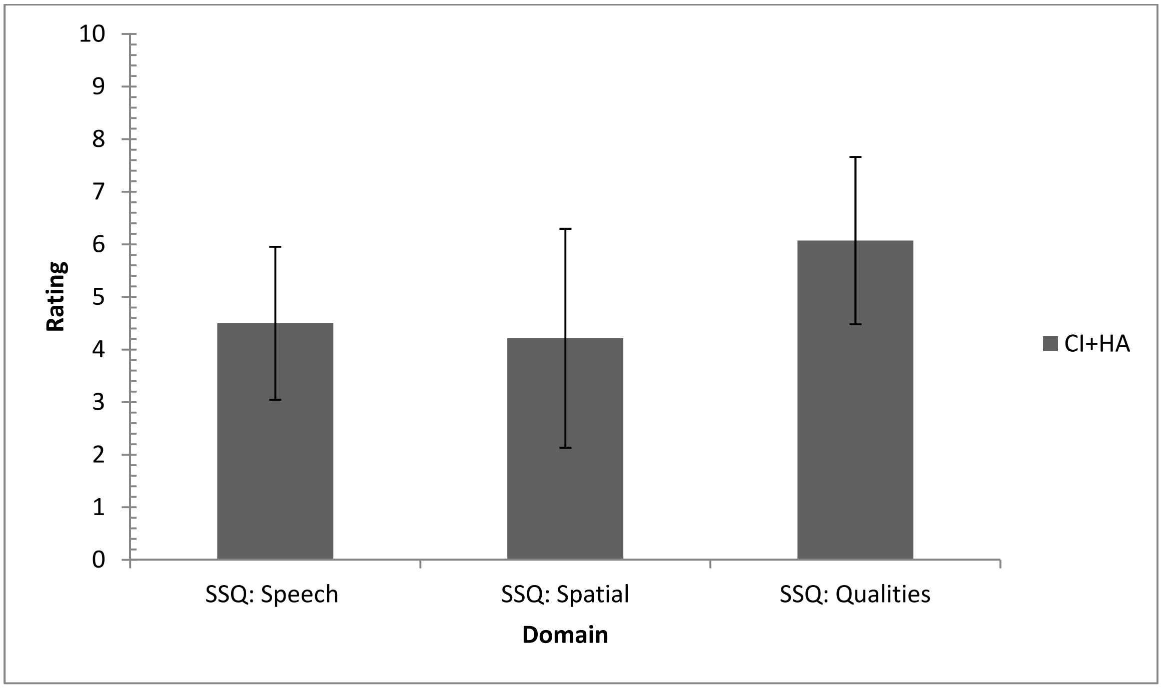

Figure 8: Mean DOSO scores for the bimodal listening condition. Error bars represent ± 1 standard deviation.

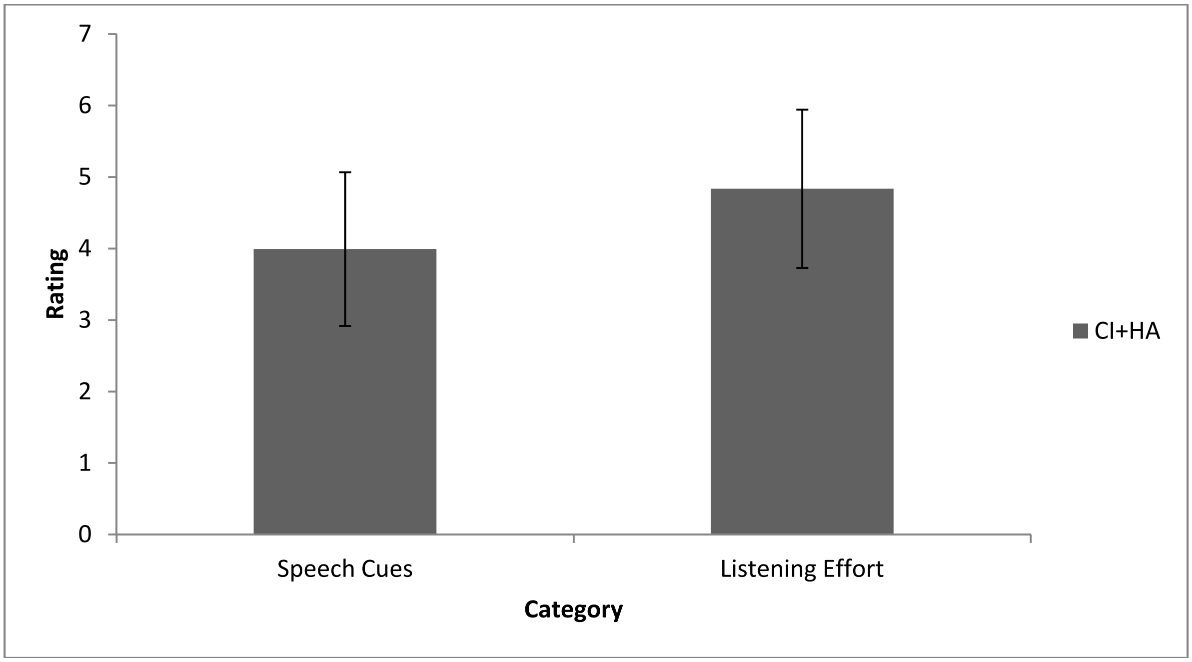

Table 4: Individual responses to the WU Bimodal Questionnaire (Questions #1-7).

Subject ID	Where Sound Is Heard When Wearing CI Only	Where Sound Is When Wearing HA By Itself	Where Sound Is When Wearing CI and HA	Time Spent Wearing CI Only	Time Spent Wearing HA Only	Percentage of Time CI and HA Worn Together	Noticed Difference In Hearing Without HA
P1	CI Left Ear	HA Right Ear	HA Right Ear	None of the time	Some of the time	85	Yes
P2	CI Left Ear	HA Right Ear	Center	None of the time	None of the time	100	Yes
P3	CI Right Ear	HA Left Ear	Center	Some of the time	Some of the time	80	Yes
P4	CI Right Ear	HA Left Ear	Center	Some of the time	Some of the time	100	Yes
P5	CI Left Ear	HA Right Ear	Center	None of the time	None of the time	100	Yes
P6	In Your Head	HA Left Ear	Center/In Your Head	Some of the time	Some of the time	98	Yes
P7	CI Left Ear	HA Right Ear	In Your Head	Some of the time	Some of the time	95	Yes
P8	CI Left Ear	HA Right Ear	HA Right Ear/CI Left Ear	Some of the time	None of the time	100	Yes
P9	CI Right Ear	HA Left Ear	Center	None of the time	None of the time	100	Yes
P10	CI Right Ear	Not Sure	Not Sure	None of the time	None of the time	100	Yes
P11	In Your Head	HA Right Ear	In Your Head	None of the time	None of the time	100	Yes
P12	In Your Head	HA Right Ear	In Your Head	Most of the time	None of the time	80	Yes
P13	Center	HA Right Ear	Center	None of the time	None of the time	100	Yes
P14	In Your Head	In Your Head	In Your Head	Some of the time	Some of the time	80	Yes

Table 5: Individual responses to WU Bimodal Questionnaire (Questions #8-15).

Subject ID	Benefit when wearing CI alone	Benefit when wearing HA alone	Benefit when wearing both devices together	Which device is louder?	Degree of satisfaction with your current hearing level (CI+HA)	Describe how sound is different when wearing **just the CI** on versus wearing both devices.	Do you ever intentionally wear a device alone?
P1	1	1	5	HA	5	*I cannot understand when wearing only implant.*	Yes - HA
P2	5	5	6	HA	5	*Sounds are jumbled and restricted.*	No
P3	1	10	10	CI	10	*Sounds are less.*	Yes - HA
P4	5	5	10	CI	10	*The same, however, people sound more like chipmunks & hearing doesn't seem as normal…*	Yes - HA
P5	5	3	7	CI	10	*I don't always know where the sound is coming from when I don't have the HA on.*	Yes - CI
P6	6	1	8	CI	2	*With the cochlear only, speech is understandable. Conversation within small group is possible.*	Yes - CI
P7	6	3	10	CI	5	*Not as natural; Tinny, Brash.*	Yes - CI
P8	10	3	10	CI	10	*It is much louder, however it is more mechanical sound, not natural.*	Yes - CI
P9	1	1	5	HA	9	*Identifying location of source of sound is more difficult. Sound is less discernable.*	No
P10	4	2	10	CI	7	*Things are not "full" enough.*	No
P11	1	1	10	HA	10	*It is softer and harder to hear. CI alone is still not as "natural" sounding.*	No
P12	8	2	10	CI	8	*I can hear a lot better but I hear better with both of them.*	Yes - CI
P13	6	4	9	HA	8.5	*The sound is much more unnatural, e.g. "tinny" or electronic*	No
P14	5	1	10	CI	8	*I hear everything, but I also think that all sounds are at the same volume…*	Yes - HA

Table 6: Association between bimodal performance on objective measures and subjective reports. Correlation coefficients (r) were computed for objective test performance across subjective report ratings.

Pearson Correlation Coefficients, N = 13 Prob > |r| under H0: Rho=0					
Subjective Reports Objective Tests	**SSQ: Speech**	**SSQ: Spatial**	**SSQ: Qualities**	**DOSO: Speech Cues**	**DOSO: Listening Effort**
CNC	0.206 0.499	0.027 0.929	0.2157 0.479	-0.275 0.364	0.471 0.105
Talker Discrimination Task	0.376 0.206	-0.383 0.197	0.073 0.813	-0.010 0.973	-0.166 0.587
UW-CAMP	0.095 0.757	0.200 0.513	0.381 0.200	-0.037 0.905	-0.368 0.216
Reaction Time Task	-0.178 0.561	0.017 0.956	-0.137 0.656	-0.256 0.399	-0.134 0.663
ANL	0.183 0.549	0.227 0.456	0.469 0.106	0.196 0.521	-0.631 0.021

Appendix: WU Bimodal Questionnaire

Please answer each question as best you can.

1. When wearing the cochlear implant by itself, where do you think you hear sound? (circle your answer)

Right Ear Left Ear Center In Your Head

2. When wearing the hearing aid by itself, where do you think you hear sound? (circle your answer)

Right Ear Left Ear Center In Your Head

3. When wearing the cochlear implant and hearing aid together, where do you think you hear sound? (circle your answer)

Right Ear Left Ear Center In Your Head

4. How often do you wear your cochlear implant by itself? (circle your answer)

All the time Most of the time Some of the time None of the time

5. How often do you wear your hearing aid by itself? (circle your answer)

All the time Most of the time Some of the time None of the time

6. What percentage of the time do you wear the hearing aid with your cochlear implant (from 0% to 100%)?

7. Do you feel you hear differently when you *do not* have the hearing aid on? (circle your answer).

No Yes

If 'Yes', then how is hearing different, with the hearing aid?

8. Rate how much benefit you receive when wearing the cochlear implant by itself, v*ersus* wearing both devices together.

Not at all Somewhat Extremely
1-------------------------------------5--10

9. Rate how much benefit you receive when wearing the hearing aid by itself, *versus* wearing both devices together.

Not at all Somewhat Extremely
1-------------------------------------5--10

10. Rate how much benefit you receive when wearing both devices together.

Not at all Somewhat Extremely
1-------------------------------------5--10

11. Which device (cochlear implant or hearing aid) is louder? (circle your answer)

Cochlear implant Hearing aid

12. Rate your degree of satisfaction with your current hearing level when wearing both devices.

Not at all Somewhat Extremely
1-------------------------------------5--10

13. Describe how sound is different when wearing just the hearing aid on *versus* wearing both devices.

14. Describe how sound is different when wearing just the cochlear implant on *versus* wearing both devices.

15. Do you ever intentionally wear only one device? **No** **Yes**

If "**Yes**", which device do you wear, and in what situations?
Device worn alone: __________ Situation(s): __________